FERMILAB-Pub-04/040-E

Localized Field Reduction and Rate Limitation in Visible Light Photon Counters.

A. Bross[1], J. Estrada[1], C. Garcia[2], B. Hoeneisen[3] and P. Rubinov[1]

[1] *Fermi National Accelerator Laboratory, Batavia, Illinois 60510*

[2] *University of Rochester, Rochester, New York 14627*

[3] *Universidad San Francisco de Quito, Quito, Ecuador*

(Dated: 16-2-2004)

Abstract

We observe the effect of localized field reduction (LFR) in visible light photon counters (VLPC) by measuring the bias current of the device after a light pulse, and find it consistent with being produced by avalanches that have an average transverse dimension of $\approx 12\ \mu\text{m}^2$. The characteristic recovery time for the device after an avalanche is measured to be ≈ 3.5 ms, and is a function of bias voltage and temperature. A simple model is presented to describe the performance drop of the VLPC with rate as a consequence of LFR.

Visible Light Photon Counters (VLPC) are silicon devices that detect single photons with a quantum efficiency (Q.E.) of $\approx 80\%$ and high gain (≈ 50000). A complete description of these devices can be found in Refs. [1], [2] and [3].

A VLPC contains two active layers, an undoped silicon layer overlaying a weakly compensated arsenic-doped gain layer (density of donors $N_D \approx 10^{18}$ cm^{-3} and acceptors $N_A \approx 10^{14}$ cm^{-3}), as shown in Fig. 1. A photon incident through the contact at +V is absorbed in the intrinsic or in the gain layer, creating an electron-hole pair across a 1.12 eV gap. Under the applied bias, the electron drifts towards the positive contact and is collected. The hole moves towards the ground contact, in a series of scatterings too small to produce impact-ionization across the 1.12 eV gap. After reaching the gain layer, the hole has to acquire only about 0.05 eV to impact-ionize an As atom and create an electron-D^+ pair. The created electron can impact-ionize other As atoms, generating new electron-D^+ pairs. As this process repeats, an avalanche develops, containing thousands of electrons and D^+ charges.

The slow movement of the D^+ charges towards the negative contact of the VLPC [2] [4], and the possibility of Localized Field Reduction (LFR) due to accumulation of positive carriers has been recognized before [4]. We present an observation of LFR, and measurements of recovery time for the device, as a function of applied voltage and operating temperature. We also discuss how LFR affects the performance of the VLPC at high rate.

The experimental set-up is shown schematically in Fig. 2. A Light Emitting Diode (LED) illuminates 64 optical fibers that transmit photons to the 1.0 mm diameter pixels of Boeing HISTE VI VLPCs. The operating temperature is nominally $T = 9.0$K. A bias voltage of $V_c \approx 7.0$ V is applied through 100 kΩ resistor to each of the VLPC pixels. The VLPCs are connected to custom chips (TriP[5]) via a high density flex cable. The TriP chips integrate and amplify the signals from the VLPC so that individual photopeaks can be measured for every pixel, and these spectra determine the gain and relative quantum efficiency of the VLPCs. A monitoring circuit is used to measure the bias current of the VLPCs with sufficient accuracy and bandwidth to make the measurements presented here.

Figure 3 shows the current per pixel (i_R) when a single light pulse of 45 photoelectrons (p.e.) and 600 ns in duration is applied to the VLPC. It is evident that i_R is smaller 1 msec after the pulse than before the pulse. The dependence of i_R can be fitted to an exponential function to obtain the characteristic time τ for recovery of the dark current value before the light pulse (I_{dark}). This is shown in the inset of Fig. 3.

Generation of dark current is discussed in Ref. [6] as follows: An electron from a donor in the gain region can jump to the conduction band through a combination of thermal excitation and phonon-assisted tunneling (the Poole-Frenkel effect). This process is more probable for high electric field, i.e., near the interface of the intrinsic region, exciting electrons that do not develop a full avalanche, but produce an average bias current that is the main contribution to the dark current of the VLPC.

The drop in dark current after a light pulse in the VLPC can be understood as a direct consequence of LFR caused by the electron avalanches in the device. As D^+ carriers accumulate in the gain region, the slope of the electric field is reduced. To satisfy the boundary conditions imposed by the external voltage, the gain region extends into the drift region. The field in the intrinsic region drops and, because the generated dark current depends strongly on the field (Poole-Frenkel effect), the dark current decreases. The field in the drift region is also reduced, because it is proportional to the dark current. As the excess D^+ states are swept out of the gain region, the electric field profile approaches its steady state with time constant τ. This is shown qualitatively in Fig. 4, for representative values of the parameters of the VLPC.

Figures 6 and 5 show τ and I_{dark} as a function of temperature and bias voltage.

The Q.E. and gain in a VLPC decrease when the photon counting rate is increased [7]. A model to accommodate this effect was introduced in Ref. [6]. Based on our observations of LFR, we propose a different model, where the drop in Q.E. and gain with rate is caused by a reduction of the electric field in the region where avalanches are produced.

We consider the VLPC as an array of N cells, with each avalanche produced by a photon localized totally within one cell, and no interaction between cells. A full avalanche will remove a fraction of the electrons trapped by donors in the higher field region of that cell. When these electrons move away, the field drops, and no dark current is generated from that cell (as given in Fig. 4). After the avalanche, a cell will be filled with ionized As atoms (D^+), and the cell will recover the original electric field distribution only after the D^+ carriers move via a hopping mechanism to the electrical contact. The time τ of Fig. 3 corresponds to the recovery time for a cell, which is determined by the drift velocity of the D^+ carriers. Considering that the carries have to drift a distance of approximately 10 μm, $\tau = 3.5$ ms corresponds to a drift velocity of $v \approx 0.3$ cm/s.

The measurement of dark current shown in Fig. 3 indicate a drop of 0.07% in i_R when 45 avalanches are produced in a VLPC. In our simple model, this means that the total number of cells in the VLPC is $N = 100/0.07 \times 45 = 66,000$. The area of a VLPC pixel is $A = 0.79$ mm^2, which means that the typical area occupied by an avalanche is 12 μm^2.

To estimate the magnitude of the drop in performance with rate due to LFR, we assume that: (i) After an avalanche, the gain of a cell is reduced by 50%, and recovers with the same characteristic time τ observed for dark current; (ii) After an avalanche the Q.E. of a cell recovers as some k-th power of the gain. (This model is not intended to provide a rigorous simulation of the physics of the VLPC, but rather a tool to estimate the effect of LFR at high rates.) With these assumptions, we can estimate the gain and Q.E. as a function of rate. The results are shown in Fig. 7. The calculations, based on numerical simulations, show that $\approx 10(20)\%$ drop in performace can be expected for an input rate of 2(4) MHz. As can be seen in Fig. 7, this is consistent with the magnitude of the effect seen in the data.

In summary, we observe the effects of LFR in VLPCs with the characteristic recovery time of $\approx$ 3.5 ms (depending on bias voltage and temperature) after an avalanche. We estimate the average area for an avalanche to be 12 μm^2. Making simple assumptions for gain and Q.E. in a VLPC, we conclude that LFR can be the dominant cause of the observed reduction in VLPC performance at high rates.

We thank the U.S. Department of Energy and Fermilab for support. Fermilab is operated by the Universities Research Association Inc. under Contract No. DE-AC02-76CH03000 with the United States Department of Energy. We acknowledge the help of our colleagues: Dr. George Ginther and the DØ VLPC cassette team, the DØ mechanical and electrical engineering groups, and thank Prof. Tom Ferbel for comments on this paper.

[1] M.D. Petroff, M.G. Stapelbroek and W.A. Kleinhans, Appl. Phys. Lett. **51**, 406 (1987).

[2] G.B. Turner et al., in "Proceedings of the Workshop on Scintillating Fiber Detectors, SCIFI 93", Notre Dame University, 24-28 October, 1993, edited by R. Rutchi (World Scientific, Singapore, 1994), p. 613.

[3] Shigeki Takeuchi et al., Appl. Phys. Lett. **74**, 1063 (1999).

[4] M.G. Stapelbroek and D. Petroff, in "Proceedings of the Workshop on Scintillating Fiber Detectors, SCIFI 93", Notre Dame University, 24-28 October, 1993, edited by R. Rutchi (World Scientific, Singapore, 1994), p. 621.

[5] TriP ASIC designed by A. Mekkaoui. Described in FERMILAB-TM-2227 (Dec 2003).

[6] H.H. Hogue, in "Proceedings of the Workshop on Scintillating Fiber Detectors, SCIFI 97", Notre Dame University, November, 1997, edited by A. Bross (American Institute of Physics, Woodbury, NY), p. 345.

[7] A. Bross et al, in "Proceedings of the Workshop on Scintillating Fiber Detectors, SCIFI 97", Notre Dame University, November, 1997, edited by R. Rutchi (American Institute of Physics, Woodbury, NY), p. 332.

List of Figures

Figures

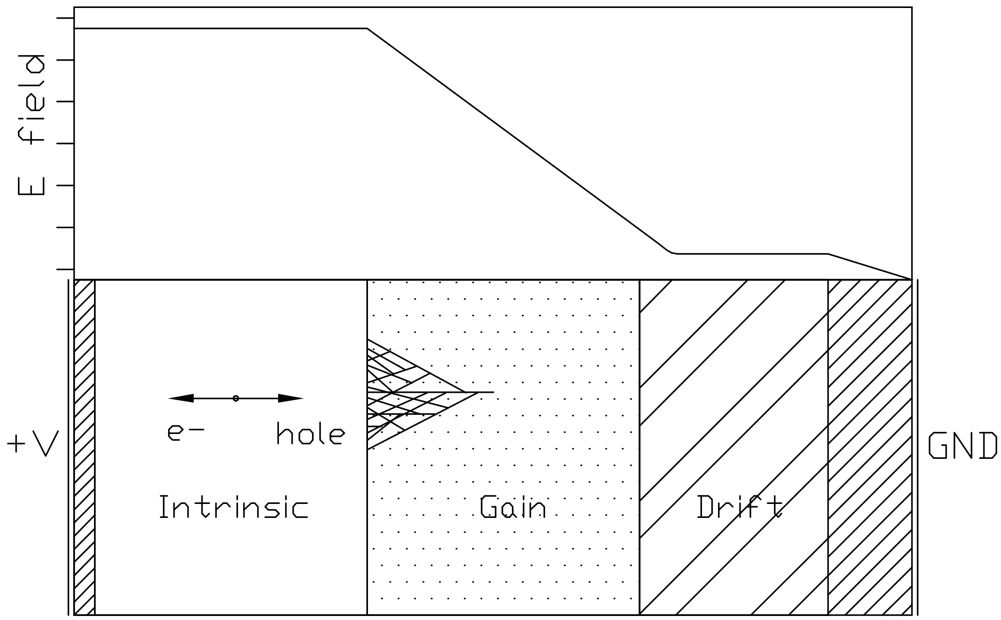

Figure 1: Schematic structure of a VLPC.

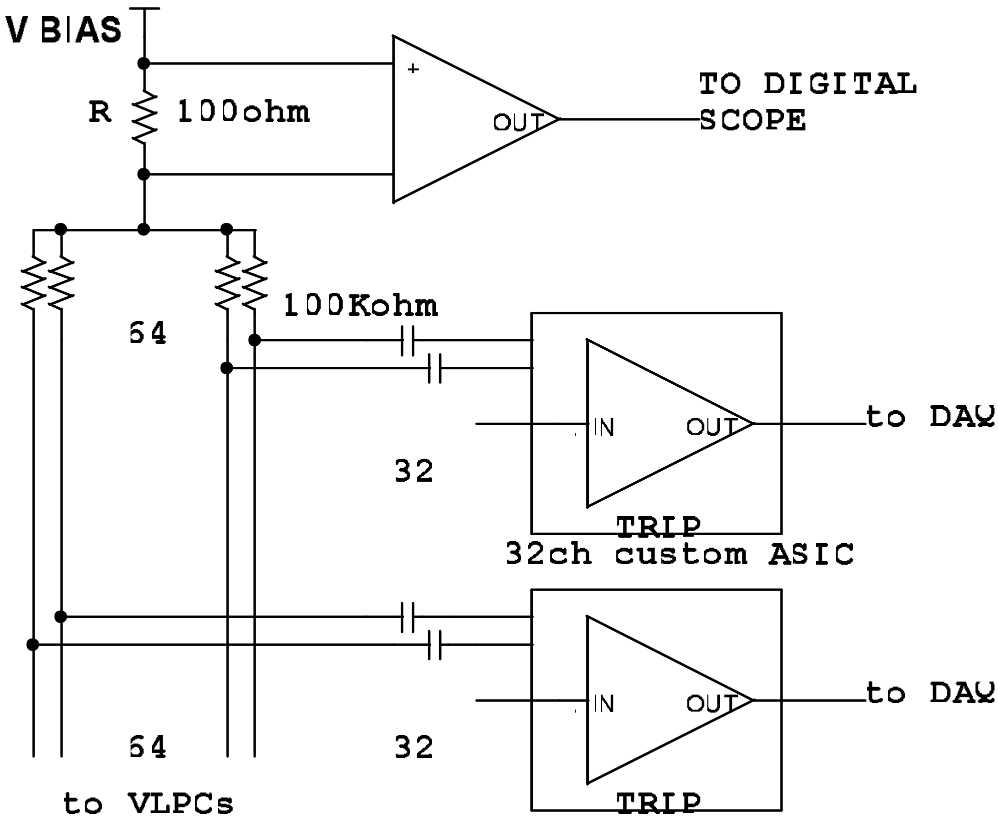

Figure 2: Schematic of the experimental set-up.

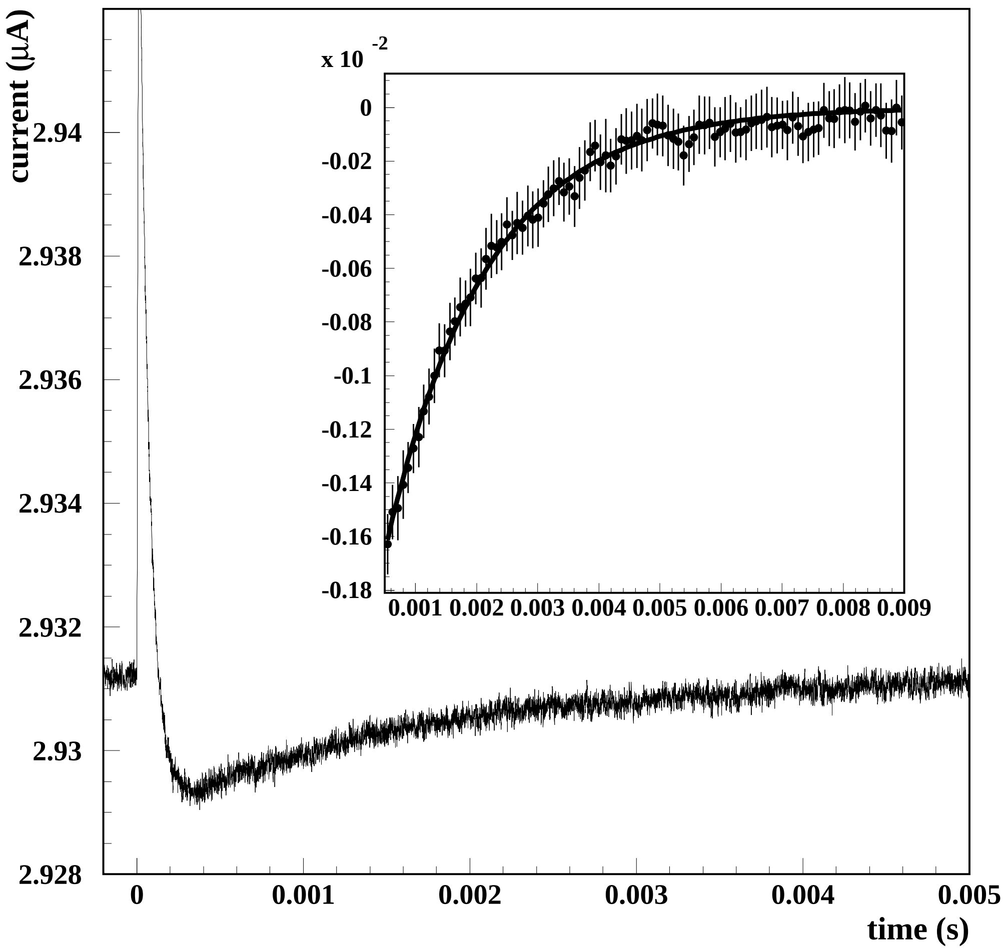

Figure 3: Current per VLPC pixel as a function of time. The temperature is $T = 9.8$K. The light pulse corresponds to 45 photo-electrons (per pixel) and has a duration of 600 ns. The bias voltage is $V_c = 6.35$V. Inset: Exponential fit to $i_{off} = i_R - I_{dark}$, where I_{dark} is the steady state dark current in a VLPC before a light pulse.

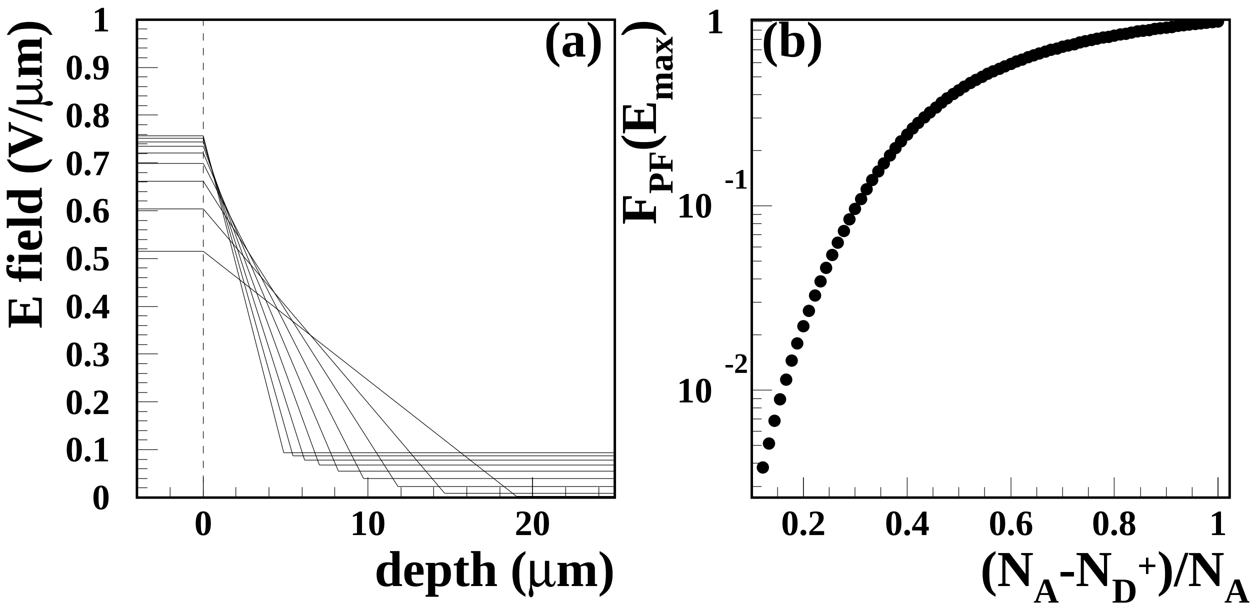

Figure 4: (a) Electric field in the VLPC calculated using representative values for the VLPC parameters [2]. The slope in the gain region is proportional to the charge density given by $N_A - N_{D^+}$, the different traces correspond $N_A - N_{D^+}$=N_A, $0.9N_A$, ... ,$0.2N_A$. (b) Poole-Frenkel factor that determines the dark current, as a function of charge density. (N corresponds to charges per unit volume.)

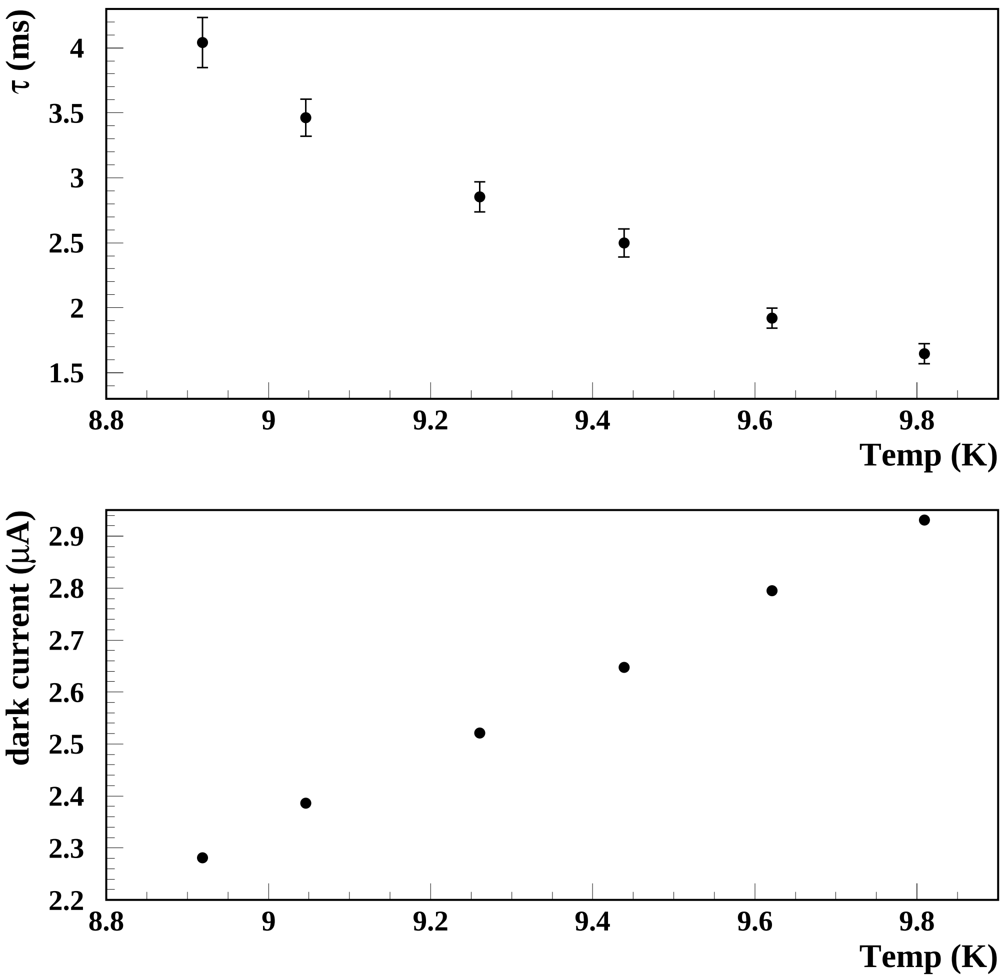

Figure 5: Time constant τ and I_{dark} as a function of temperature, for single light pulses of 45 p.e. per pixel and $V_{bias} = 6.35$V.

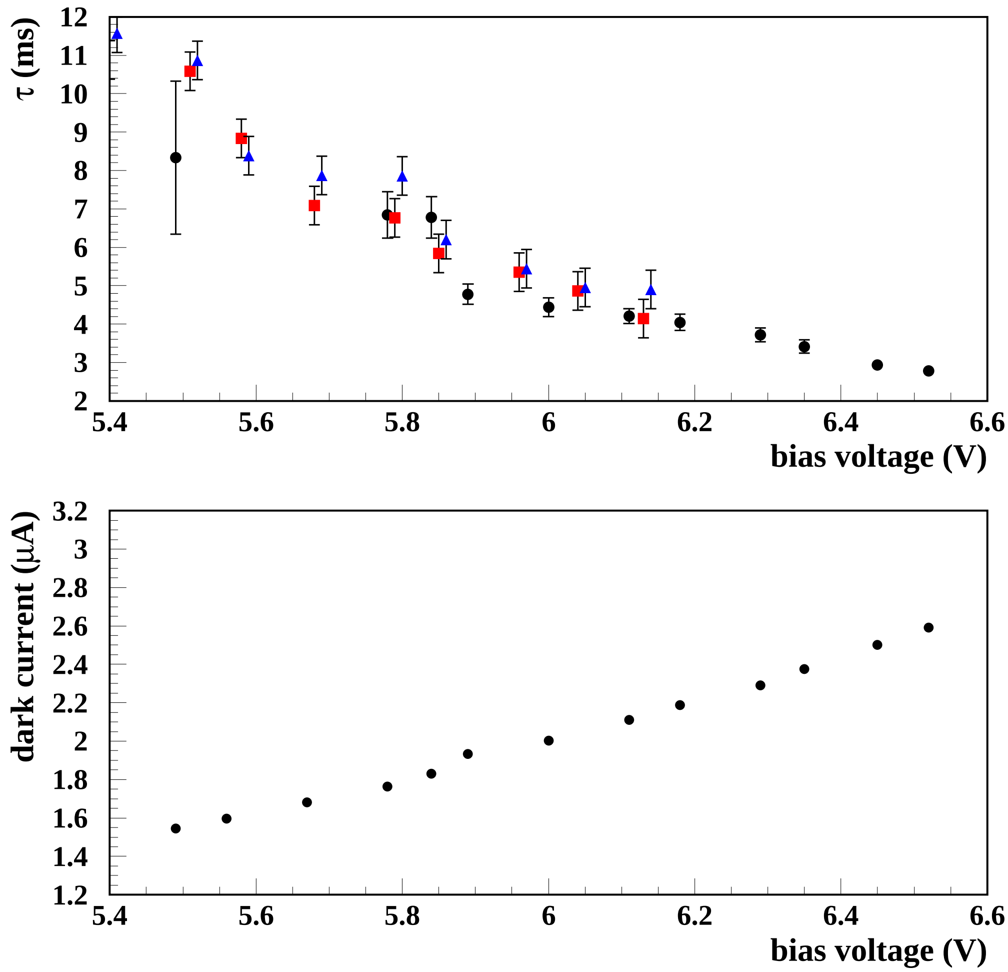

Figure 6: Time constant τ and I_{dark} as a function of bias voltage, for single light pulses of 45 p.e. per pixel and a temperature of 9 K. The symbols correspond to different voltage scans, done to verify the reproducibility of these results.

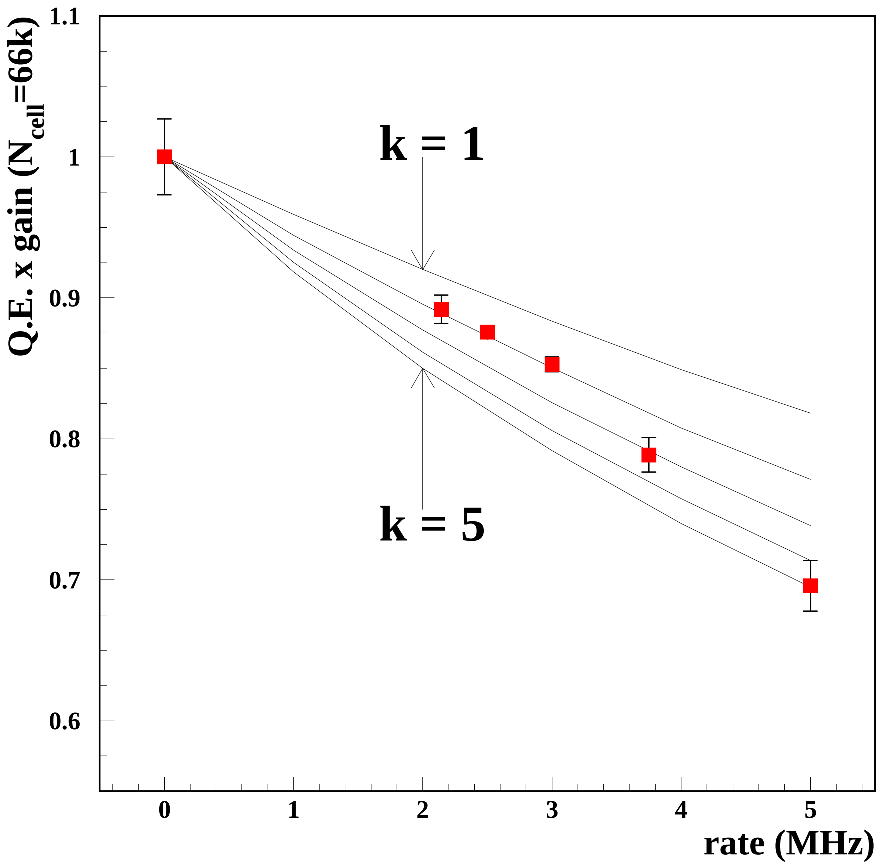

Figure 7: Product of gain and Q.E. as a function of background rate (photoelectrons per second). The data (points) are compared to simulations using our model, with different values of k.